Advancing Underwater Acoustic Communication for Autonomous Distributed Networks via Sparse Channel Sensing, Coding, and Navigation Support

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Award Number: N00014-09-1-0704
Sponsor: Department of Defense (PECASE)
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LONG-TERM GOALS

The long-term goal is to significantly advance underwater acoustic communication technologies for autonomous distributed underwater networks, through innovative signal processing, coding, and navigation algorithms. Providing highly reliable and high data rate communication links will be critical towards the development of a new era of underwater distributed networks.

OBJECTIVES

We have three objectives in this project.

1. **Advanced communication techniques of sparse channel sensing and nonbinary LDPC coding.** Underwater acoustic channels are naturally sparse, but how to effectively exploit the sparsity is a challenging task. We will investigate the recently developed "compressive sensing" algorithms for sparse channel estimation in the context of multicarrier acoustic communications. On the other hand, channel coding is one integral part of an advanced communication system, and is dispensable in approaching the theoretical limit predicted by the Shannon theory. We will thoroughly investigate nonbinary low-density-parity-check (LDPC) codes, and especially pursue fast encoding and decoding algorithms and practical implementations.
2. **High-resolution ranging and navigation.** Wideband multicarrier waveform has a dual use that it can yield precise timing information for the receiver to infer the distance from the sender. With range estimates from multiple buoys, each underwater vehicle can self localize and navigate. We will investigate ranging and tracking algorithms that achieve high positioning accuracy. We aim to integrate the communication and navigation capabilities into the OFDM modem under development, which will greatly facilitate the development of emerging underwater distributed networks.
3. **Testbed development and medium access control.** We plan to develop a network testbed to illustrate the cooperative networking scenario. We first will determine an effective medium access

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2009	**Annual**	**00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Advancing Underwater Acoustic Communication For Autonomous Distributed Networks Via Sparse Channel Sensing,Coding, And Navigation Support	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Connecticut,Electrical and Computer Engineering Department,Storrs,CT,06269**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Code 1 only

14. ABSTRACT
The long-term goal is to significantly advance underwater acoustic communication technologies for autonomous distributed underwater networks, through innovative signal processing, coding, and navigation algorithms. Providing highly reliable and high data rate communication links will be critical towards the development of a new era of underwater distributed networks.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**5**	

control protocol to improve the system throughput for multiple users equipped with high-rate OFDM modems. We will then carry out demonstrations in three settings: 1) point to point links with advanced communication techniques; 2) ranging and navigation in a setup with four buoys and one underwater node; and 3) cooperative networking in a setup with four buoys and multiple underwater nodes.

APPROACH

Our technical approach is to develop advanced signal processing algorithms to improve the robustness and increase the data rate of underwater acoustic communication. Specifically, 1) we will use compressive sensing algorithms to exploit the sparsity nature of the underwater acoustic channels, 2) we will develop advanced capacity-achieving nonbinary LDPC codes to improve the error performance, 3) we will improve the localization and navigation performance through the use of wideband OFDM waveforms, which has much increased time-resolution for ranging purposes, and 4) we will investigate effective medium access protocols along with a testbed demonstration with multiple nodes.

We work with Dr. Jie Huang from the University of Connecticut (UConn) to carry out the research tasks on sparse channel estimation and nonbinary LDPC coding. We collaborate with Drs. Zhijie Shi and Jun-Hong Cui from UConn on testbed development.

WORK COMPLETED

We have developed sparse channel estimation algorithms and advanced channel coding schemes, and have tested them using extensive data sets from three experiments:

1) RACE 08 experiment, Narragansett Bay, March 2008 (led by Dr. James Preisig)
2) GLINT08 test, Pianosa, Italy, July 2008 (through Mr. Lee Freitag)
3) SPACE08 experiment, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)

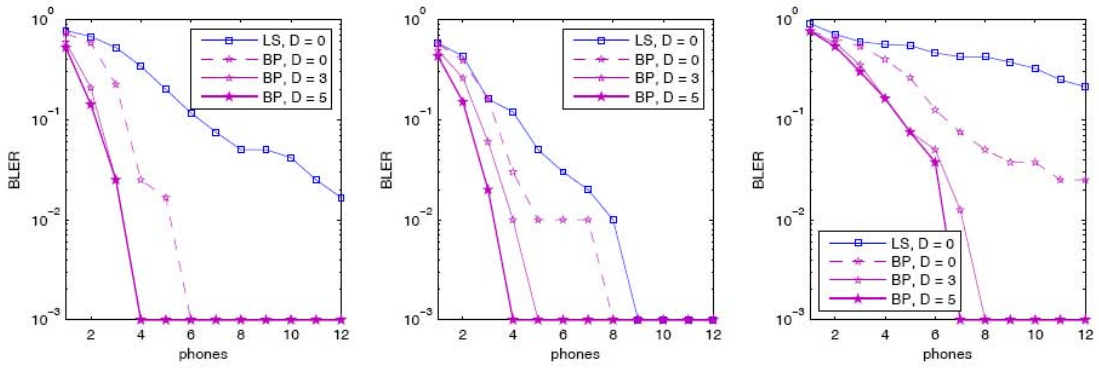
We have guided one undergraduate senior design project related to network navigation:

- Project: *Localization for underwater sensor networks*. Duration: Fall08-Spring09. Team: Patrick Carroll, Ryan McDermott, Sherwayne Gordon, John Botticello.

RESULTS

1) Sparse channel sensing. We have investigated various channel estimators that exploit channel sparsity in the time and/or Doppler domain for a multicarrier underwater acoustic system. We suggested a path-based channel model, where the channel is described by a limited number of paths, each characterized by a delay, Doppler scale, and attenuation factor, and derived the exact inter-carrier-interference (ICI) pattern. For channels that have negligible Doppler spread we showed that subspace algorithms from the array processing literature, namely Root-MUSIC and ESPRIT, can be applied for channel estimation. For channels with Doppler spread, we adopted recent compressed sensing algorithms in form of Orthogonal Matching Pursuit (OMP) and Basis Pursuit (BP), and utilized overcomplete dictionaries with an increased path delay resolution. Numerical simulation and

experimental data of an OFDM block-by-block receiver were used to evaluate the proposed algorithms in comparison to the conventional least-squares (LS) channel estimator. We observed that subspace methods can tolerate small to moderate Doppler effects, and outperform the LS approach when the channel is indeed sparse. On the other hand, compressed sensing algorithms uniformly outperform the LS and subspace methods. Coupled with a channel equalizer mitigating ICI, the compressed sensing algorithms can effectively handle channels with significant Doppler spread.



(a) Julian Date 300, S1 (b) Julian Date 300, S3 (c) Julian Date 300, S5

Figure 1: Basis-pursuit (BP) algorithms outperform the conventional least-squares (LS) drastically. Data from the SPACE08 experiment. S1 (60m), S3(200m), and S5 (1 km).

2) An OFDM design for Doppler spread channels. Underwater acoustic channels induce large Doppler drifts that result in intercarrier interference (ICI) for OFDM transmissions. Assuming that after proper Doppler compensation the residual ICI is limited to only direct neighbors, we have proposed an OFDM signal design that decouples channel estimation and data demodulation. We investigated five receivers that are categorized into three groups: (i) two receivers that ignore the residual ICI, (ii) two receivers that are based on a basis expansion model (BEM) and pursue channel estimation independently along each basis, and (iii) one receiver that is based on a path-based model. The receiver performance was compared based on data from the GLINT08 experiment and the SPACE08 experiment. The receiver based on the path-based model and a basis pursuit (BP) algorithm achieves the best performance, followed by the ICI-ignorant and BEM versions of BP. The least-squares channel estimation performs the worst, especially in combination with the BEM. The BEM based receivers are often inferior to the ICI-ignorant counterparts, except for conditions with very large Doppler spread. This implies that there exists a trade-off between ICI compensation and the estimation accuracy of the much increased number of BEM parameters. On the contrary, the path-based channel model facilitates ICI compensation without increasing the number of model parameters, by exploiting the sparse representation in the joint delay-Doppler domain.

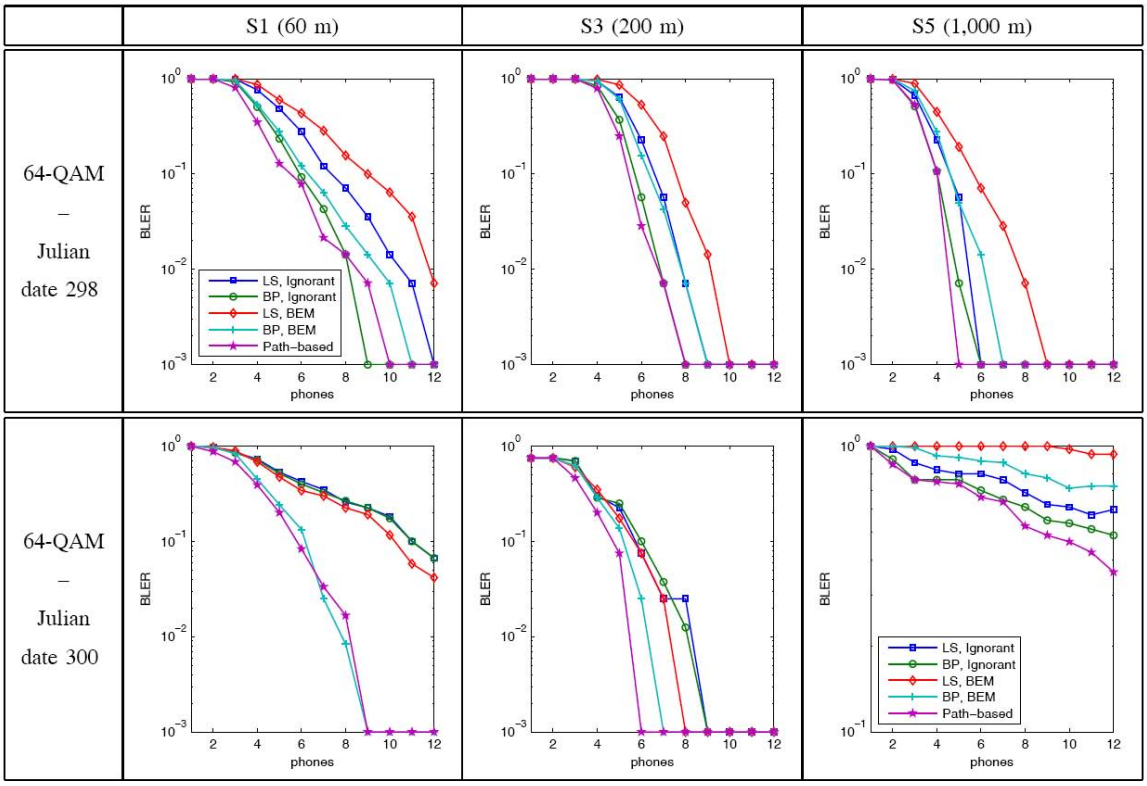
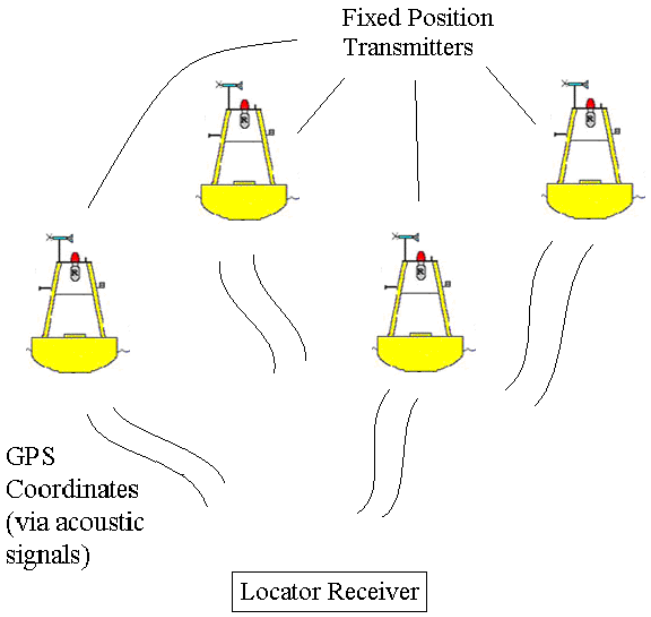


Figure 2: Performance results for SPACE'08 experiment, 64-QAM, on two specific days.

3) Nonbinary LDPC coding. We have proposed a novel method to design nonbinary multiple-rate LDPC codes with underlying quasi-cyclic structure and constant blocklength. Starting from the highest-rate code, nonzero entry splitting in the parity check matrix was used to render the column weight consistent for a bunch of code rates. The obtained codes can be encoded in linear time in parallel. The proposed method can be used to design multiple-rate systems using nonbinary coded modulation. Simulations demonstrate that the proposed codes can achieve both good water-fall and error-floor performance.

4) Localization. A senior design team has carried out a project focused on node self-localization in an underwater network. As shown in the figure below, four buoys broadcast messages periodically. The receiver receives the broadcasting messages, and measures the transmission delay from each transmitter to the receiver, and then calculates its own position. This is similar to the GPS concept, but work in an underwater environment, where the radio GPS is ineffective.

In our lake test April 2009, we have only used two transmitters and one receiver in a short distance. Although a full lake demonstration has not been accomplished, this project has been useful in establishing proof of concept for an underwater localization technique. It provides a framework of thinking which could be expanded upon and improved for implementation in working systems. One senior design student, Mr. Patrick Carroll, has decided to further pursue a M.S. degree on this topic.



IMPACT/APPLICATIONS

The success of our project will have a deep impact. Providing high-data-rate and reliable acoustic communication with navigation functionalities, our project will directly contribute to the development of distributed autonomous underwater networks that are of great interest to Navy, e.g., the AUV/UUV/Glider networks.

PUBLICATIONS

1. Z. Zhou, J. H. Cui, and S. Zhou, “Efficient Localization for Large-Scale Underwater Sensor Networks,” Ad Hoc Networks, 2009 [in press].
2. C. R. Berger, S. Zhou, J. Preisig, and P. Willett, “Sparse Channel Estimation for Multicarrier Underwater Acoustic Communication: From Subspace Methods to Compressed Sensing,” IEEE Trans. Signal Process., May 2009 [submitted].
3. S. Mason, C. R. Berger, S. Zhou, K. R. Ball, L. Freitag, and P. Willett, “Receiver Comparisons on an OFDM Design for Doppler Spread Channels,” IEEE J. Ocean. Eng., July 2009 [submitted].
4. J. Huang, S. Zhou, and P. Willett, “Structure, Property, and Design of Nonbinary Regular Cycle Codes,” IEEE Transactions on Communications, revised Aug. 2009 [submitted].
5. J. Huang, L. Liu, W. Zhou, and S. Zhou, “Nonbinary Multiple-Rate LDPC Codes with Underlying QC Structure and Constant Blocklength,” IEEE Trans. on Communications, July 2009 [submitted].

HONORS/AWARDS/PRIZES

Shengli Zhou received the UTC Professorship in Engineering Innovation, 2008-2011. The award sponsor is United Technologies Corporation (UTC).